



The Need for Robust, Consistent Methods in Societal Exergy Accounting



Tânia Sousa^{a,*}, Paul E. Brockway^b, Jonathan M. Cullen^c, Sofia Teives Henriques^d, Jack Miller^e,
André Cabrera Serrenho^c, Tiago Domingos^a

^a MARETEC - Marine, Environment and Technology Center, Department of Mechanical Engineering, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal

^b Sustainability Research Institute, School of Earth and Environment, University of Leeds, LS2 9JT, UK

^c Department of Engineering, University of Cambridge, Cambridge CB2 1PZ, UK

^d Department of Economic History, Lund University, Box 7083, S-220 07 Lund, Sweden

^e Sussex Energy Group, Science Policy Research Unit, Jubilee Building, University of Sussex, Brighton BN1 9QE, UK

ARTICLE INFO

Article history:

Received 3 August 2016

Received in revised form 24 March 2017

Accepted 14 May 2017

Available online 24 May 2017

Keywords:

Energy efficiency

Exergy accounting

Energy end-uses

Societal exergy metabolism

ABSTRACT

Studies of societal exergy use have the common aim of tracing the flow of exergy along society, and are used to gain insights into the efficiency of energy use and linkages to economic growth. However, their methodological approaches vary greatly, with significant impacts on results. Therefore, we make a review of past studies to identify, synthesize and discuss methodological differences, to contribute to a more consistent and robust approach to societal exergy accounting. Issues that should be taken into account when making methodological options are discussed and key insights are presented: (1) For mapping of primary inputs and useful exergy categories, the inclusion of all natural resources is more consistent but it has the cost of not being able to distinguish the various energy end-uses in the production of materials. (2) To estimate primary electricity, none of the methods currently used is able to capture simultaneously the efficiency of the renewable energy sector, the environmental impact and the efficiency of energy use in society. (3) To estimate final-to-useful exergy conversion efficiencies, standard thermodynamic definitions should be used because the use of proxies fails to distinguish between increases in exergy efficiency and increases in the efficiency of providing energy services.

© 2017 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Contents

1. Introduction	12
1.1. Energy Flows Along the Energy Supply Chain	12
1.2. Moving From an Energy to Exergy-based Approach	12
1.3. Societal Exergy Analysis: Applications	13
1.4. Rationale and Aim for This Paper	13
2. Materials and Methods	14
2.1. Societal Exergy Studies: Basic Methodology	14
2.2. Meta-analysis of Societal Exergy Studies	14
3. Results	15
3.1. Inputs	15
3.1.1. Energy Resources (ER) vs Natural Resource (NR) Methods	15
3.1.2. Food and Feed	15
3.2. Estimating Primary Exergy of Electricity	15
3.3. Exergy Efficiencies	16
3.3.1. Allocation and Granularity of Energy Resource Mapping	16
3.3.2. Exergy Efficiency in Transport	18
3.3.3. Exergy Efficiency in High Temperature Heating (HTH)	18

* Corresponding author.

E-mail address: tania.sousa@tecnico.ulisboa.pt (T. Sousa).

4.	Discussion and Conclusions	18
4.1.	Aims, Inputs and End-uses.	18
4.2.	Electricity	19
4.3.	Granularity and Consistency of Exergy Efficiencies	19
	Acknowledgements	19
	Appendix A. Appendix	19
	References.	19

1. Introduction

1.1. Energy Flows Along the Energy Supply Chain

Modern societies use vast amounts of primary energy in the form of fossil fuels, uranium and renewable energy. Whereas in the past this energy might have been used directly, for example by burning fuels for heat or using wind to provide work, today energy is commonly upgraded into more concentrated and transportable forms through a complex network of conversion processes in the energy supply chain. Fig. 1 shows these conversion processes, from primary energy (e.g. crude oil), to final energy (e.g. diesel) to useful energy (mechanical work) and then to energy services (e.g. freight transport). Useful energy is the energy that remains at the end the energy supply chain, at the last point of energy use. It is the energy that people actually engage with everyday: the heat that is delivered from an electric radiator, the mechanical work delivered to the tyres of a car, or the electro-magnetic radiation coming from a light bulb. Useful energy is then delivered into 'passive systems' (Cullen et al., 2011) (e.g. the body, tyres, and brakes of the car, excluding the engine and drive mechanism) where it is ultimately lost as unwanted heat, in exchange for energy services such as thermal comfort, illumination and transport.¹ In contrast to useful energy, energy services are not necessarily measured in energy units, e.g., freight transport is measured in ton.km.

The scale and efficiency with which useful energy is delivered in a society is important, as this determines the amount of primary energy required. Using an energy analysis approach, based on the first law of thermodynamics (conservation of energy), one can calculate the energy flows and the energy efficiency of each conversion along the specific energy chains, where energy efficiency is defined (Patterson, 1996) by Eq. (1):

$$\text{Energy efficiency, } \eta = \frac{\text{Useful output of a process}}{\text{Energy input to a process}} \quad (1)$$

1.2. Moving From an Energy to Exergy-based Approach

In such a "First Law Approach", we can only see flows of conserved quantities (energy), and so we don't have a real understanding of the transformations. This can be obtained by including the second law of thermodynamics, which recognises that in energy conversion processes, not all input energy can be converted into physical work. The measure of these thermodynamic losses is in terms of 'exergy destruction'. Exergy is "available energy" and takes into account the quality of the energy by measurement of the potential of an energy flow to do physical work until it achieves equilibrium with the environment (Reistad, 1975). The distinction between exergy and energy is illustrated in Fig. 2. Imagine 100 kWh of water at 160 °C and 100 kWh of water at 25 °C in an environment at 25 °C. With water at 160 °C, an ideal power

¹ The internal combustion engine of the car is a conversion device because it converts chemical energy (actively, intentionally) into the more useful form of mechanical work, while the body, tyres, and brakes of the car, excluding the engine and drive mechanism, are the passive system because they dissipate (not intentionally) the mechanical work into low grade heat via rolling resistance, air resistance and friction to provide the energy service of transport.

cycle could deliver close to 35 kWh of mechanical power, while water at 25 °C would be useless. Thus exergy is a measure of thermodynamic energy quality.

Societal exergy studies have the potential for providing an overall view of exergy flow in societies, with two major advantages: providing a theoretically consistent and unified metric for all exergy flows including all natural resources; and pinpointing the locations and magnitudes of the exergy losses. The benefits of shifting the focus from an energy to exergy perspective has been recently acknowledged by several important organisations, (APS, 2008; Brockway et al., 2016; Laitner et al., 2012).

Exergy efficiency, identifies the (mis)match between the potential to do work of the input flow (exergy input) and the actual amount of work (exergy output) accomplished by energy conversion, as shown in Eq. (2):

$$\text{Exergy efficiency, } \varepsilon = \frac{\text{Useful exergy (output)}}{\text{Exergy input}} \quad (2)$$

Thus, the theoretical maximum exergy efficiency of a process is, by definition, always 100%. Exergy efficiencies are helpful to evaluate the improvement potential of each conversion process and to compare between processes, as shown in Fig. 3. For example, heating a house with an electric radiator has a first law (energy) efficiency of 100%, as all electricity is converted to heat. Yet this is an inefficient process, because low temperature heat is a lower quality form of energy compared with

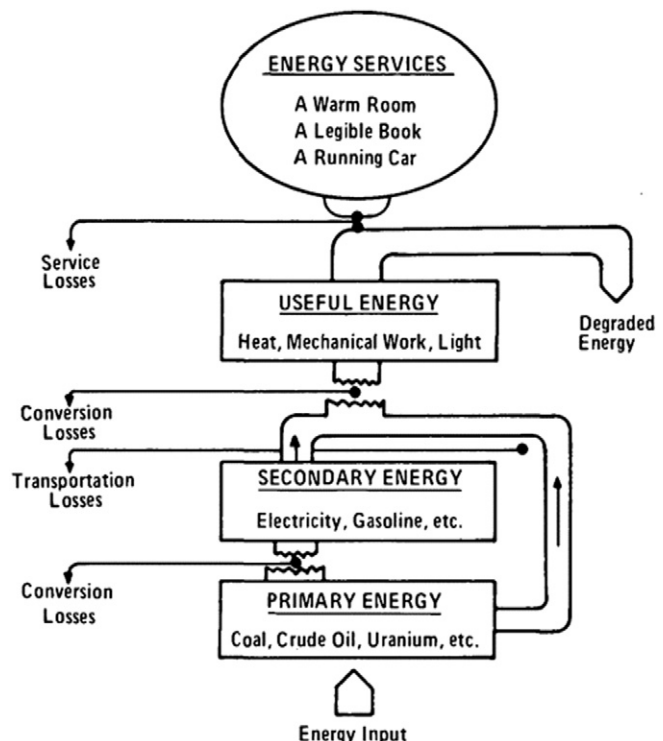


Fig. 1. Energy supply chain: from primary energy to energy services (Häfele, 1977).

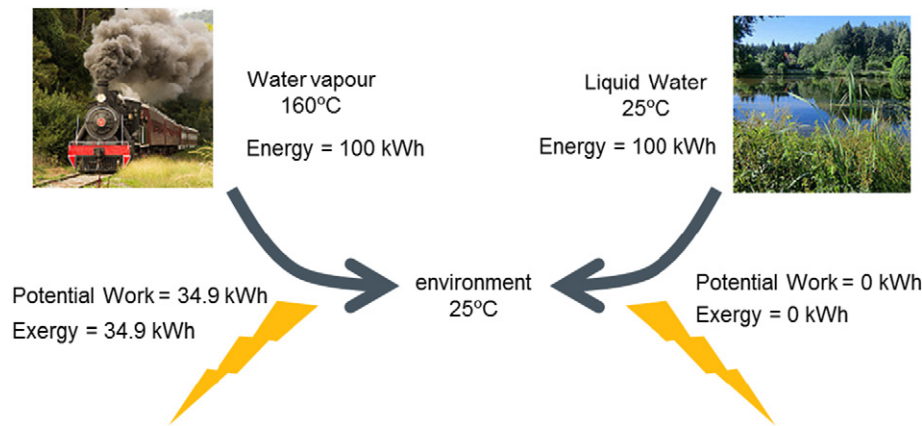


Fig. 2. Exergy versus energy: equal amounts of energy can deliver different maximum amounts of useful work (exergy). Locomotive photo “Selva Valdiviana” by Guillermo Andre under CC by 2.0 and lake photo “Small lake in the sun” by Reinhard Link under CC by SA-2.0.

electricity, in terms of its ability to do work. Thus, the exergy efficiency of the same process is only 5%. Quantifying exergy, rather than energy, reveals a much richer picture of an energy system.

1.3. Societal Exergy Analysis: Applications

The concept of a societal exergy study is not new, having been discussed and debated among academics for more than forty years (Reistad, 1975), and many attempts have been made to quantify the amount of primary, final and useful exergy used at the sector, national or global levels. Societal exergy analyses have been used mainly for two types of applications.

The first type of application is to characterize historical or forecast energy consumption. At the global level, Nakićenović et al. (1996) and Cullen and Allwood (2010b) estimated global aggregate primary to useful exergy efficiencies of 10% for 1990 and 11% for 2008 respectively, while Ertesvag's (2001) meta-study shows the range of estimated national primary to useful exergy aggregate efficiencies as being between 10% and 30%. Also, at the global level, Sassoon et al. (2009) performed an exergy analysis including all natural resources to estimate exergy and carbon flows. For the last century, Warr et al. (2010) found that aggregate primary to useful exergy efficiencies in Austria, UK, US and Japan increased from less than 5% to values that range from 11% (US) to 20% (Japan) in the 1970, stabilizing or even slightly declining afterwards. The trend for stabilization or decrease of aggregated exergy efficiencies has been found for Japan (Williams et al., 2008) due to the use of progressively less efficient primary energy resources (electricity being delivered by hydropower first and later by fossil power plants) and in the US (Brockway et al., 2014) and Portugal (Serrenho et al., 2016) due to structural shifts to lower efficiency consumption (e.g., transport). This efficiency dilution effect is an important result only revealed by societal exergy analysis. The potential future declines in the rate of exergy efficiency improvement have been taken into account by Brockway et al. (2015) to project China's primary energy demand to 2030.

The second type of application is to study the role of energy (exergy) in economic growth. This can take various angles, such as studying the evolution of long-term exergy intensities or integrating exergy as a production factor. Serrenho et al. (2014, 2016) explored the long term patterns of useful exergy intensity for Portugal from 1856 to 2009 and for 15-European countries between 1960 and 2009, concluding respectively that useful exergy intensity is roughly constant and that year-on-year variation depends only on the variation of high temperature heat and residential heat uses. Ayres and Warr (2005) and Warr and Ayres (2012) analysed useful exergy as a production factor alongside canonical labour and capital concluding that it significantly reduces exogenous growth (the Solow residual). More recently, Santos et al. (2016) were

able to drastically reduce the Solow residual and maintain the standard cost shares for labour and capital using useful exergy as a production factor.

1.4. Rationale and Aim for This Paper

Whilst societal exergy accounting studies have the common aim of tracing the flow of exergy through society, their methodological approaches vary greatly with significant impacts on exergy efficiencies, as shown, for example, by the differences in overall exergy efficiency (21% vs. 10%) obtained for the US in 1970 respectively by Reistad (1975) and Warr et al. (2010). To date no paper attempts to draw out and discuss these methodological differences as its central aim. We set out to review, systematize and discuss the different approaches taken for calculating societal exergy with the aim of providing understanding and clarity to those using or undertaking future societal exergy studies. Section 2 synthesizes the results of a meta-analysis to past studies, where differences between methodological approaches are identified. Section 3 discusses these results, outlining advantages and disadvantages of each approach. Section 4, concludes and provides recommendations to improve the quality of societal exergy studies.

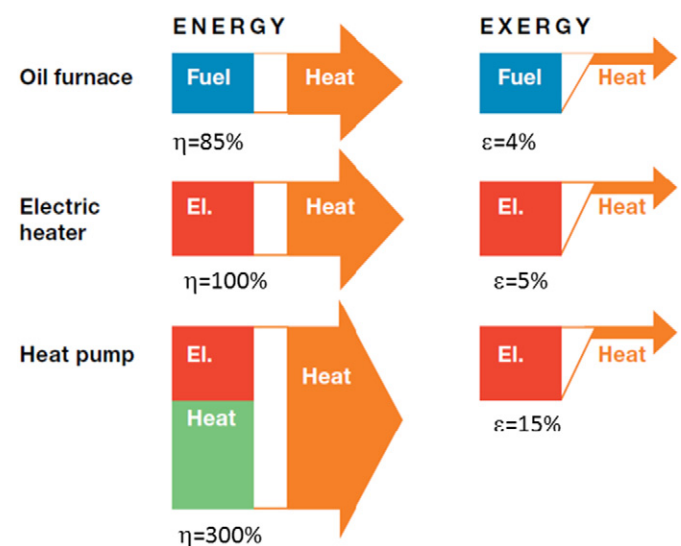


Fig. 3. Energy (first law) versus exergy (first and second law) efficiencies for different heat technologies (Dewulf et al., 2015).

2. Materials and Methods

2.1. Societal Exergy Studies: Basic Methodology

We need first to set out the main analytical steps in societal exergy studies, in order to understand the data that we seek in the meta-analysis. The first key step is the definition of the boundary and the exergy flows. Defining the boundary in principle necessarily implies defining the exergy flows – they are all the flows that cross that boundary (inputs and outputs); different boundaries lead to the definition of different flows. In practice, and according to the aim of the analysis, we may disregard some flows, either because they are comparatively negligible or because there is a direct link between incoming and outgoing flows and so they effectively cancel.

The input (primary exergy) flows, can be classified as mass, i.e., mostly “intrinsic” chemical or nuclear energy (fossil fuels, biomass, nuclear fuels), mechanical energy (e.g. wind) and/or potential energy, (e.g. hydro), radiation (solar) and heat (geothermal). Some classification schemes consider primary electricity (one form of electromagnetic work).

The output (useful exergy) flows are directly connected to the energy services provided. The most significant useful exergy flows have a somewhat natural physical grouping into end-uses: heat; mechanical work/energy; light. Mechanical work, delivered by what are frequently called “prime movers” (e.g., (Smil, 1994), can also be naturally divided in stationary vs. mobile (the latter being “transport”) and inanimate vs. animate (draught animals and humans). Some classification schemes consider electricity itself (Ayres et al., 2003), forcing us to remove the corresponding outputs obtained from that electricity (heat, mechanical work, light).

We note that both for input (primary exergy) and output (useful exergy) flows, electricity is an issue, for two main reasons. First, because,

there are (very) different methods to account for primary exergy associated with primary electricity. Second, because electricity is the most “fungible” form of energy; it can easily be transformed into any other form of energy, which means that it is difficult to allocate correctly electricity to end-uses. So, here we consider two issues regarding electricity, at opposite ends of its transformation chains: (i) how to account for it when it is generated from renewable resources, i.e., the accounting of primary exergy; (ii) how to allocate electricity to different end uses, i.e., the useful exergy flows that it generates.

Having set the boundary and the exergy flows, the next step is to estimate exergy conversion efficiencies through to the useful exergy stage. However, a central problem is that energy data at the useful stage is not systematically collected, translating to the need to use estimated exergy efficiencies, which in turn has generated different methodologies for certain end uses. The end-uses with key methodological differences regarding the estimation of exergy efficiencies are high temperature heat uses and transportation, and so these are reviewed in the meta-analysis in Section 2.2.

2.2. Meta-analysis of Societal Exergy Studies

Based on these issues, we reviewed past studies, and synthesized in Table 1 for each study: (1) the aim and (2) the methodological options regarding the definition of the input and output flows, the allocation of flows to end-uses, the estimation of efficiencies and the treatment of electricity. The classification of aims in Table 1 is intimately related with the applications that these studies pursue (see Section 1.1). The first type of application includes studies that look at exergy efficiency (EF), energy transitions (ET) and make forecasts of energy demand (FED) while the second type includes studies that focus on economic growth (EG).

Table 1
Summary of selected societal useful exergy studies (ordered by date of study).

	Country	Time	Aim	Property	Stages	Inputs	Electricity	Exergy efficiency		
(Reistad, 1975)	USA	1970	EF	EN/EX	P-F-U	ER	PSM	2ER	CAR	LIT
(Wall, 1987)	Sweden	1980	EF	EX	P-F-U	NR & Sun	RCM		RAT	LIT
(Wall, 1990)	Japan	1985	EF	EX	P-F-U	NR & Sun	RCM		RAT	LIT
(Rosen, 1992)	Canada	1986	EF	EN/EX	P-F-U	ER	RCM	2ER	CAR	LIT
(Schaeffer and Wirtshafter, 1992)	Brazil	1987	EF	EN/EX	P-F-U	ER	PCM	AER	CAR	LIT
(Wall et al., 1994)	Italy	1990	EF	EX	P-F-U	NR & Sun	RCM		RAT	LIT
(Nakićenović et al., 1996)	World	1990	EF	EN/EX	P-F-U	ER	PCM	AER	CAR	LIT
(Rosen and Dincer, 1997)	Turkey	1993	EF	EN/EX	P-F-U	ER	RCM	2ER	CAR	LIT
(Hammond and Stapleton, 2001)	UK	1965–2000	EF	EX	P-F-U	ER	RCM	2ER	CAR	LIT
(Ayres et al., 2003)	USA	1900–1998	EG	EX	P-F-U	NR	PSM	AER	RAT	MPG
(Williams et al., 2008)	Japan	1900–2000	EF	EX	P-F-U	ER	RCM	–	RAT	LF
(Warr et al., 2008)	UK	1900–2000	EG	EX	P-F-U	ER	RCM	AER	RAT	LF
(Cullen and Allwood, 2010a)	World	2005	EF	EX	P-F-U	ER	RCM	SER	CAR	LIT
(Warr et al., 2010)	UK, Austria, Japan and US	1900–2000	EG	EX	P-F-U	ER & FF	RCM	AER	RAT	LF
(Brockway et al., 2014)	UK, US	1960–2010	EF	EX	P-F-U	ER & FF	RCM	AER	RAT	MPG
(Serrenho et al., 2014)	EU-15	1960–2009	EF/EG	EX	F-U	ER & FF	–	AER	CAR	LF
(De Stercke, 2014)	World	1900–2010	ET	EN/EX	P-F-U	ER	PSM	2ER	–	LIT
(Brockway et al., 2015)	China	1971–2010	FED	EN/EX	P-F-U	ER & FF	RCM	AER	RAT	MPG
(Serrenho et al., 2016)	Portugal	1860–2009	EF/EG	EX	F-U	ER & FF	–	AER	CAR	LF
(Guevara et al., 2016)	Mexico	1960–2009	EF/EG	EX	F-U	ER & FF	–	AER	CAR	LF

Key

- Aim (EF – exergy efficiency; ET – energy transitions; EG – economic growth; FED – forecasting energy demand).
- Property (EN – energy; EX – exergy).
- Energy Stages (P – primary; F – final; U – useful).
- Inputs (ER – energy resources excluding non-energy uses; NR – natural resources Sun – sunlight radiation for passive solar heating; FF – food and feed). (Discussed further in Section 3.1)
- Method for primary electricity (PSM – partial substitution method; PCM – physical content method; RCM – resource content method). (Discussed further in Section 3.2)
- Key differences in methods for estimating exergy efficiency. (Discussed further in Section 3.3)
 - Detail in the allocation of final exergy (2ER – two resources only; AER – all energy resources; SER – all energy resources, allocated to end-use devices, passive systems and energy services).
 - High temperature heat efficiency method (RAT – ratio between minimum exergy and exergy used; CAR – product of first law efficiency and Carnot factor).
 - Transport efficiency method (MPG – function of miles per gallon; LF – product of ideal thermal efficiency and loss factors; LIT – engineering estimate or from literature).

Methodological differences between studies are identified for: (1) the energy stages considered (primary, final and useful, or only final and useful); (2) the energy inputs (energy resources (ER), natural resources (NR), the Sun, and food and feed (FF)); (3) the method used to estimate the primary exergy of electricity; and (4) the definition of exergy efficiencies for different conversion processes. Table 1 then serves as the basis for more detailed discussions in the remaining paper (Sections 3 and 4).

Finally, a note on the studies that was not included in our meta-analysis. Societal exergy studies that use the Extended Exergy Approach (Chen and Chen, 2009; Ertesvag and Mielnik, 2000) pioneered by Wall and Sciubba (1994) and Sciubba (2005) were not included because they take into account exergy measures of physical capital, labour and environmental remediation costs that are beyond the scope of this paper.

3. Results

3.1. Inputs

3.1.1. Energy Resources (ER) vs Natural Resource (NR) Methods

There are two main set of approaches to input flows (column “Inputs” in Table 1 for references) in societal exergy accounting (Ertesvag, 2001). The first set of approaches focus only on energy resources (ER – traditional energy resources, FF – food and feed and Sun – non-commercial energy resources). The second focuses on natural resource (NR) and takes into account not only the exergy in energy resources but also other natural resources such as the harvested yields of forest and agriculture crops, and metals such as iron ore.

The energy resources (ER) accounting approach considers only traditional ‘energy resources for energy use’ such as electricity, biomass, coal and fossil fuels (Ertesvag, 2001). However, excluding energy resources that are used for non-energy services can be tricky because the distinction between energy resources used for energy or non-energy purposes is sometimes difficult to make (Wall et al., 1994). For example, metallurgical coke is used in steel-making for three functions: as a heating fuel; as a reducing agent in the iron ore to iron reaction; and as a ‘feedstock’ embedded in the iron and the steel.² The food and feed (FF) approach considers resources for muscle work (food and feed). The “Sun” approach considers renewable energy that is not commercialized such as wind used by sail boats or sunlight used for passive solar heating. These studies follow the conversion of energy resources from the primary through to the final and useful level, where they are transformed into an energy service.

The NR accounting approach is based on the fact that exergy can be used as a common metric for all natural resources. Exergy can be extracted as the material returns to the average reference state, normally taken as the concentration in the earth’s crust. For example, steel can be oxidized to iron ore releasing approximately 6.7GJ/ton (Fruehan et al., 2000). This is the exergy embedded (not embodied)³ in the steel. The exergy embedded in steel, and other recyclable materials, can be used as input partially replacing the need for exergy, e.g., making steel from iron-ore via the integrated route uses on average three times as much energy per tonne of steel as making steel from recycled scrap in an electric furnace (Worldsteel, 2015). The NR approach therefore has the advantage of treating recycling processes more consistently. However, it fails to provide a good description of energy end-uses in contrast to the energy resource accounting approach since the distinction between the several energy end-uses such as heat or mechanical work

needed to produce materials such as food, wood and paper, steel and chemicals disappear; they become merged and embedded into the material. This is illustrated in Fig. 4 for the cement industry. In the energy resources (ER) accounting approach, the inputs are the energy resources. The outputs (e.g. high temperature heat) are estimated knowing the allocation of these inputs to end-uses (e.g. coal used in clinker kilns for high temperature heat) and efficiencies of the energy transformation devices (e.g. efficiency of the clinker kiln). In the natural resources (NR) accounting approach, the inputs are all the natural resources while the outputs are the exergies embedded in the intended products (clinker and cement).

3.1.2. Food and Feed

Draught animals exist almost solely to provide mechanical work.⁴ Therefore, it is widely accepted that their total intake of feed should be accounted for, whether it is used for work or just for keeping the animal alive at all times. Historical values of the gross calorific value⁵ of their feed intake (Serrenho et al., 2016; Wirsenius, 2000) are usually estimated from recommended digestible feed intake, draught animals’ headcount and from quantitative and qualitative information on average weight and working effort (Kander and Warde, 2011).

However, there is greater controversy about human work, and a variety of approaches have been proposed in the literature (Fluck, 1992) to estimate food intake associated with it. Many studies include all consumed food, either considering only the working population (Pimentel and Pimentel, 2008) or the whole population (Kander et al., 2013; Serrenho et al., 2014; Serrenho et al., 2016). They argue that even if not all the food is consumed while working, it is indispensable for the labour force to receive nutrition to be kept alive between working hours; and that even if a share of the population is not economically active, they occupy positions in society that are necessary for it to function (Warde, 2007). Some have suggested including, as an energy input, only the increase in food intake that occurs due to working activity (e.g. 500 cal per day per worker), that is, excluding energy requirements for body survival and for small activities such as hygiene, eating, standing and even leisure activities (Brockway et al., 2014; Smil, 1994). Others have suggested considering the proportion of food that is consumed by the organism, both for doing work and staying alive, but only during working hours (Stanhill, 1980). The two latter approaches referred argue that it’s important to distinguish the food needed for doing work from the caloric intake that is used for other types of needs.

Regarding primary exergy associated with muscle work, the approach followed by Brockway et al. (2014) and Warr et al. (2008) is to consider the appropriated phytomass (Wirsenius, 2000), i.e., the necessary production of living organic plant material (e.g. crops and pasture) to provide for food (final exergy associated with human muscle work) and feed (final exergy needed for animal muscle work).

3.2. Estimating Primary Exergy of Electricity

There is broad agreement on the methodology used to estimate the primary exergy for fossil-fuel based conversion to electricity, since as most occurs in central power stations, the losses from primary to final energy are commonly reported. For nuclear-based conversion to

² The small fraction of carbon (3.5–4.5%) embedded in iron is considered a material input, but about half of this is later oxidized to CO₂, to meet the final carbon content specification for steel (0.12–2.0%).

³ Embodied energy calculations capture the entire upstream energy input, and allocate this to the material flow, the physical energy embedded in the material is the lower bound for the embodied energy.

⁴ Some draught animals such as cows provide also dairy products, but adjustments on feed intake can be made to take that into account.

⁵ The gross energy (GE) value of a given feed is the amount of heat released when it is burned in a bomb calorimeter and represents the maximum available work of the feed. Serrenho et al. (Serrenho et al., 2016. Structure and dynamics of useful work along the agriculture-industry-services transition: Portugal from 1856 to 2009. Structural Change and Economic Dynamics 36, 1–21.) using data from Wirsenius (Wirsenius, S., 2000. Human use of land and organic materials: Modelling the turnover of biomass in the global food system. Department of Physical Resource Theory (Phd Thesis), Gothenburg.) calculated that gross energy is 1.54 times higher than metabolized energy. This relation can change, depending on the composition of the feed. For example, hay has a lower digestible content than grain.

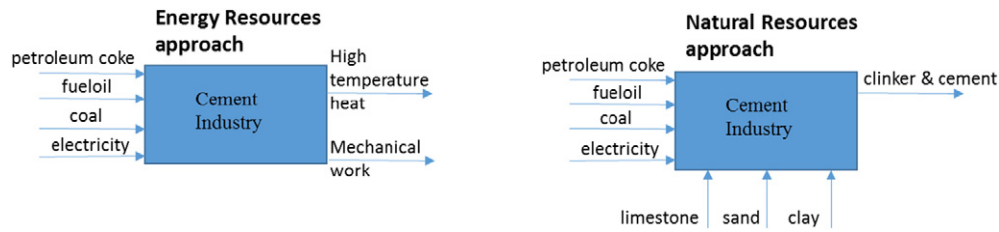


Fig. 4. The inputs and outputs of the cement industry in the energy resources (ER) approach and the natural resources (NR) approach.

electricity, the primary exergy that societal exergy studies consider is the thermal exergy content of the steam. A more consistent approach across natural resources would probably require the estimation of the exergy of the nuclear fuel. However, in contrast to thermo-mechanical or chemical exergy, there is no consensus regarding the estimation of nuclear exergy.

However, societal exergy studies differ in the way they take into account primary energy associated with electricity from hydro, solar, wind, geothermal, waves, etc., (column “Electricity” in Table 1 for references). Let us take as an example the accounting of primary energy associated with hydroelectricity using three different measures: 1. the coal equivalent; 2. the change in kinetic and potential energy of a mass of flowing water and 3. electricity produced. First, the coal equivalent is a measure of the energy (specifically, the enthalpy) of the fuel needed to produce the same amount of electricity in conventional power plants. This method – called the Partial Substitution Method (PSM) – is used by the EIA (US Energy Information Administration) and BP, and historically by the IEA. Second, the change in kinetic and potential energy of the water is based on the assumption that this is the primary energy as it is found in nature – the Resource Content Method (RCM). This is easily expanded to other renewable resources. Third, the electricity produced is the primary energy associated with hydroelectricity based on the rationale that primary energy is the first form of commercial available energy. This is called Physical Content Method (PCM) and is used by the IEA.

The methods mentioned so far refer to primary energy and not primary exergy. These two quantities are roughly equal for all resources with the exception of solar radiation and geothermal heat; in this case the temperature of the heat flow is needed to convert energy to exergy.

The three methods identified from the meta-analysis yield different estimates of primary exergy inputs. To illustrate this, imagine a country in which electricity generating capacity is comprised solely of coal power plants, dams (hydroelectricity), and wind farms. In a rainy year, electricity is produced from hydro and wind only, while in a dry year hydro-electricity is replaced by coal-derived electricity. Table 2 shows how total primary energy estimated for both years is sensitive to the energy resources used and the method chosen: it would remain the same with the PSM and it would vary significantly with the PCM and RCM.

The RCM emphasizes changes in the efficiency of converting renewable resources like kinetic wind energy or radiation in electricity. This is an important issue because, for each specific conversion technology (e.g. photovoltaic solar panels), the higher the efficiency, the lower the capital and land allocated to produce the same amount of electricity which are both scarce resources. The PSM estimates primary energy for renewable and non-renewable electricity, in the same way, neglecting the structure of the energetic sector, i.e., the energy resources used to produce electricity. It is an adequate choice to emphasize changes in the final energy used and to estimate the societal energy intensity. Aggregated primary energies estimated using RCM or PSM are not a good measure of environmental impacts because these methods do not differentiate between renewable and non-renewable resources. On the contrary, PCM attributes a lower value of primary energy to renewable electricity when the resource used has no commercial value. Primary energy can decrease by a shift from non-renewable to renewable electricity production but it does not take into account the efficiency of the renewable electricity production.

3.3. Exergy Efficiencies

3.3.1. Allocation and Granularity of Energy Resource Mapping

Exergy efficiencies in societal exergy studies are not always estimated in a consistent manner due to the diversity and differences in the granularity of end-uses between sectors and lack of data (examples will be given in Sections 3.3.2 and 3.3.3). These inconsistencies together with differences in the level of disaggregation in the allocation of energy-resources to end-uses have an impact on overall efficiencies. For example, the introduction of cooling by Brockway et al. (2014) and Palma et al. (2016) as a differentiated end-use, reduced overall exergy efficiencies because electrical cooling was a significant end use that had a low efficiency (3–5%). The issue of sectoral/data disaggregation is particularly acute in the case of electricity.

To estimate exergy efficiencies, we need to first allocate final energy resources to energy end-uses (e.g., coke used in the iron and steel industry is attributed to the disaggregated end-use category of high temperature heat). Some early societal exergy studies consider only two distinct energy resources, electricity and fuel (2ER) in the allocation to end-use devices or end-uses within sectors while others consider all

Table 2
Primary Exergy (PE) associated with different accounting methods.

	Rainy year				Dry year			
	Hydro	Wind	Coal	Total	Hydro	Wind	Coal	Total
Electricity produced	60 GWh	40 GWh	0	100 GWh	0	40 GWh	60 GWh	100 GWh
PE (PSM)	60 GWh 40%	40 GWh 40%	0	250 GWh	0	40 GWh 40%	60 GWh 40%	250 GWh
PE (RCM)	60 GWh 90%	40 GWh 45%	0	156 GWh	0	40 GWh 45%	60 GWh 40%	239 GWh
PE (PCM)	60 GWh 100%	40 GWh 100%	0	100 GWh	0	40 GWh 100%	60 GWh 40%	150 GWh

Notes

1. The same amount of electricity (final energy) is assumed in all three methods, i.e., 100 GWh.
2. The PSM assumes a 40% efficiency while the conversion from coal to electricity is also 40%.
3. The RCM assumes 90% and 45% efficiencies for hydro and wind, respectively.

Table 3

Adapted from (Ford et al., 1975) by (Serrenho et al., 2016). Exergy efficiencies for pairs final exergy resource (column) and useful exergy end-uses (line) where the temperatures of thermal reservoirs are such that T_1 (hot reservoir) $> T_2$ (warm reservoir) $> T_0$ (environmental temperature) $> T_3$.

Final exergy	Useful exergy			
	Work		Fuel	Heat Q_1 from hot reservoir at T_1
	W_{in}		B	$Q_1(1 - \frac{T_0}{T_1})$
Work	W_{out}	$\epsilon = \eta = \frac{W_{out}}{W_{in}}$	$\epsilon = \frac{W_{out}}{B} \approx \eta$	$\epsilon = \frac{W_{out}}{Q_1(1 - \frac{T_0}{T_1})} = \frac{\eta}{1 - \frac{T_0}{T_1}}$
Heat Q_2 added to warm reservoir at T_2	$Q_2(1 - \frac{T_0}{T_2})$	$\epsilon = \frac{Q_2}{W_{in}}(1 - \frac{T_0}{T_2}) = \eta(1 - \frac{T_0}{T_2})$	$\epsilon = \frac{Q_2}{B}(1 - \frac{T_0}{T_2}) \approx \eta(1 - \frac{T_0}{T_2})$	$\epsilon = \frac{Q_2(1 - \frac{T_0}{T_2})}{Q_1(1 - \frac{T_0}{T_1})} = \eta \frac{1 - \frac{T_0}{T_2}}{1 - \frac{T_0}{T_1}}$
Heat Q_3 extracted from cool reservoir at T_3	$Q_3(\frac{T_0}{T_3} - 1)$	$\epsilon = \frac{Q_3}{W_{in}}(\frac{T_0}{T_3} - 1) = \eta(\frac{T_0}{T_3} - 1)$	$\epsilon = \frac{Q_3}{B}(\frac{T_0}{T_3} - 1) \approx \eta(\frac{T_0}{T_3} - 1)$	$\epsilon = \frac{Q_3(\frac{T_0}{T_3} - 1)}{Q_1(1 - \frac{T_0}{T_1})} = \eta \frac{\frac{T_0}{T_3} - 1}{1 - \frac{T_0}{T_1}}$

energy resources (AER). Typically, a higher level of disaggregation for the energy resources is linked with more categories of end-uses. Cullen and Allwood (2010a) go further by quantifying and tracing the useful exergy flows (motion, heat and other end-uses such as lighting and cooling) to final exergy services (SER) such as transport, hygiene, thermal comfort, communication, illumination, sustenance and structure.

Several studies (Hammond and Stapleton, 2001; Reistad, 1975; Rosen, 1992; Rosen and Dincer, 1997) use aggregate exergy efficiencies for each sector that depend on the relative amount of each energy vector (fuel and electricity) and end-uses considering only heating and mechanical power. Later studies estimate exergy efficiencies by first allocating each energy resource per sector or economic activity to an end-use, and typically include a higher number of end-use categories including light, other electrical uses, muscle work and cooling (Ayres et al., 2003; Serrenho et al., 2014; Serrenho et al., 2016; Warr et al., 2010; Warr et al., 2008). Nakićenović et al. (1996) estimate 1990 global energy and exergy efficiencies by allocating energy vectors to end-uses within each sector. These efficiencies were subsequently updated to 2005 using IEA trend data for the energy intensity in each sector by Cullen and Allwood (2010a).

Aggregated exergy efficiencies can be estimated from the primary (or final) to useful stages of energy use. When evaluating exergy efficiencies between the final and useful stages of energy use, care has to be taken since (thermo)electricity (i.e., electricity derived from combustion of coal, biomass, oil or natural gas) has a much lower primary to final efficiency than other final energy fuels (such as diesel or gasoline). Additionally, there are cases where there is a two-stage final conversion, for example, a residential diesel-fuelled generator where diesel is converted to electricity and then electricity is converted to an end-use, e.g., light. In these cases, the final-to-useful aggregate efficiency should consider the final energy resource (diesel) and the end-use (light).

Standard final-to-useful exergy efficiencies (see Eq. (2)) are defined in Table 3 for several pairs of final exergy inputs (e.g. work such as electricity or fuel such as food or coal) and useful exergy outputs (e.g. heat and mechanical and muscle work). Useful exergies outputs are given on the left end-side for each row and final exergies inputs are given on the top for each column where “W” is used for work, “Q” for heat and “B” for chemical exergy.⁶ All exergy efficiencies, ϵ , depend on energy efficiencies, η . For devices that convert one form of chemical, electrical or mechanical energy to another, ϵ is equal to η . For devices that have heat as an input or output then heat must be downgraded into equivalent units of mechanical work (Cullen and Allwood, 2010a), i.e., the work that could be done with the heat flow using a Carnot power cycle. Heat as an input at temperature T_1 is converted to exergy (3rd column) with the Carnot efficiency $\eta_{Carnot} = 1 - T_0 / T_1$ where T_0 is the temperature of the environment. While heat as an output at T_2 is converted to exergy (2nd row) with $\eta_{Carnot} = 1 - T_0 / T_2$. For devices

whose aim is to extract heat, the exergy of the heat flow is the work a Carnot refrigerator cycle would need as an input to extract it. “Cold” as output at temperature T_3 is converted to exergy (3rd row) with the inverse of the refrigeration Carnot efficiency $\beta_{Carnot} = T_3 / (T_0 - T_3)$.

Exergy efficiencies for muscle work also can be estimated using Table 3 (1st column and 1st row). For working animals, we need information on their typical power delivery and number of hours working. Draught animals can produce a power output of 0.3–0.8 kW, depending on their type and weight (Smil, 1994; Stout, 1990). Hours of use depend on the region and historical time period,⁷ but it is common to assume that they only sustain this level of power for 4 or 5 h per day over the year (Stout, 1979). The resultant efficiencies⁸ of draught animals given in historical studies vary between 4 and 13% (Ayres and Warr, 2009; Serrenho et al., 2016). For human labour, the average power output is estimated at 75 W for the working day (Stout, 1990). Estimated primary (or final) to useful efficiencies will, of course, be highly variable depending on which approach is adopted for estimation of primary (final) exergy input (see discussion in Section 3.1.2).

However, Table 3 does not synthesize all exergy efficiencies. For example, the expressions in this table cannot be directly applied to the conversion of electricity into light, sound and information because the useful output cannot or is not typically measured in energy units. For these cases, exergy efficiencies are given by Eq. (3):

$$\epsilon = \frac{W_{min}}{W_{max}} = \frac{Output/W_{max}}{Output/W_{min}} = \frac{\eta}{\eta_{ideal}} \quad (3)$$

Also, there are cases where an expression in this table could be used but for some reason (e.g. lack of data) is not. In these cases a proxy for the exergy efficiency is used and the useful exergy is estimated as the product between this proxy and final exergy. Examples in the transport and heating sectors are discussed in Sections 3.3.2 and 3.3.3.

Whilst data on proxies for exergy efficiencies – such as miles per gallon or lumens per watt – may often be more readily available than data needed for exergy efficiencies, the translation between the two is not straightforward, given that they are measuring different things, at different stages of the energy provision chain. For the most part, energy services (and hence the use of these hybrid unit proxies) extend beyond

⁷ Manual work usually did not exceed 2000 h/per capita/year in traditional agriculture and draught animals put in even fewer hours. For example, a study of Danish agriculture indicates that horses were used 1220 h per year on average in 1938, see Schroll, 1994. Energy flow and ecological sustainability in Danish agriculture. Agriculture, Ecosystems and Environment 51, 301–310.

⁸ For illustration purposes, we describe a typical way of calculating efficiencies: a 500 kg horse working with average effort in the 1920s needed about 35 GJ of digestible feed per year (Hansson, 1928. Husedjurenas utfodring. Dess teoretiska grunder och ekonomiska genomförande. C.E. Fritze, Stockholm. Assuming that the gross exergy of the feed is 1.54 times this value (Wirsénus, 2000. Human use of land and organic materials: Modelling the turnover of biomass in the global food system. Department of Physical Resource Theory (PhD Thesis), Gothenburg.) will translate into a gross exergy of 53.9 (= 35 × 1.54) GJ. Assuming a power of 0.75 kW (Smil, 1994. Energy in world History. Westview Press, Colorado.) and 1400 h of work per year gives a work output of 1050 (= 1400 × 0.75) kWh, i.e., 3.78 GJ, and an overall efficiency of 7% (= 3.78/53.9).

⁶ The exergy of fuels is assumed to be similar to the heating-value (HV), where HV is between the Low and High Heating Values (Klein and Nellis, 2012. Thermodynamics. Cambridge University Press).

the boundaries of exergy analyses to date (Fig. 1). In addition, the use of these approaches does not distinguish between efficiency changes in the final to useful conversion (car engine) and in the passive system (e.g. the mass or shape of the vehicle when using miles-per-gallon as a proxy for transport efficiency).

3.3.2. Exergy Efficiency in Transport

For vehicles, energy is transformed along the energy chain, from crude oil to refined fuel, to combustion in the engine, to mechanical rotational work, through the gearbox and driveshaft to the tyres. Losses occur at each conversion stage, but it is at the tyres (where ‘rubber meets the road’) that the final loss of exergy occurs, and where we should define the boundary for useful exergy. Here the thrust force delivered to the vehicle (passive system) is resisted by rolling and aerodynamic drag forces, and dissipated as low-grade heat.

However, whilst straightforward to explain, studies vary regarding the way exergy efficiencies are estimated for transport (see column “Transport Efficiency” in Table 1 for references). The standard approach, Loss Factors approach (LF), estimates exergy efficiencies as being equal to first law efficiencies (see Table 1). First law efficiencies depend on loss factors and the ideal first law efficiency which is a function of the compression ratio (Carnahan et al., 1975). Whilst this LF approach is consistent with our definition of useful exergy boundary efficiencies, the studies apply the Carnahan et al. (1975) loss factors to their whole times-series, due to the lack of more recent obtainable data (at least to the authors). This assumption that the loss factors are constant over their analysis period is a significant constraint to this approach. Due to this flaw, other studies used a different approach (MPG), and assume exergy efficiency is proportional to fuel economy (measured in miles-per-gallon). For example, Brockway et al. (2014) developed an approach to correlate mpg data with available US drive-train data (Thomas, 2014) to produce a log-curve based estimate of exergy efficiency based on historical fuel efficiency. However, this does not differentiate between improvements in the conversion device and the large changes that have occurred in the passive systems (SUVs, aerodynamics, etc.). Despite this, the MPG approach can be developed further since there is good data available on the exergy efficiency of engines and drive-trains.

All of this matters, since the methodology chosen causes considerable differences in estimated efficiencies: three separate studies estimated UK diesel vehicle exergy efficiencies between 1960 and 2010 – whereby Warr et al. (2008) and Serrenho et al. (2014) used the LF approach while Brockway et al. (2014) used the MPG approach. The LF-based final-to-useful exergy efficiencies for passenger cars remained fairly constant at around 10% (Warr et al., 2008) and 12–13% (Serrenho et al., 2014), whilst Brockway et al. (2014)’s time-varying MPG-based approach estimated that exergy efficiencies doubled, from 10% to 20%.

3.3.3. Exergy Efficiency in High Temperature Heating (HTH)

There are differences regarding the methodology used to estimate exergy efficiencies for high temperature heating processes (column “HTH Efficiency” in Table 1 for references). The standard Carnot-based approach (CAR) calculates exergy efficiencies as a function of first law efficiencies and the Carnot temperature ratio (see Table 3). In this approach, the granularity in specifying service temperatures for different industries has a significant impact on aggregated exergy efficiencies (Palma et al., 2016). An alternative ratio-based approach (RAT) considers that there are proxies that can be used as HTH exergy efficiencies in material production in industry such as (1) the ratio of theoretical minimum to actual exergy consumption in an endothermic process or (2) the ratio between the embedded exergy and the actual exergy used to produce a unit of the intended output(s) – akin to the NR method referred to earlier in Section 3.1. An example given by Ayres et al. (2003) shows the US steel industry with a 50% estimated efficiency, based on a total exergy inputs of 22.6 GJ/ton versus the embedded

exergy of 6.62 GJ/ton for rolled steel and 4.28 GJ/ton for other useful by-products. An added complexity is to decide how many industries to consider: some use the steel industry as a model for HTH efficiency gains (Ayres et al., 2003; Warr et al., 2008), while others take the two largest heat consuming industries (e.g. steel and petrochemicals) and then apply their weighted efficiency as a proxy for the high temperature heat efficiency in all industry (Brockway et al., 2014).

These differences can have significant impacts: three studies of high temperature heat in the UK between 1960 and 2010 estimated primary-to-useful exergy efficiencies increasing from 15% to 22% (Brockway et al., 2014), from 18% to 27% (Warr et al., 2008) or from 36% to 45%⁹ (Serrenho et al., 2014). The standard method of estimating HTH exergy efficiencies is more consistent with the way of obtaining exergy efficiencies for other uses and with our definition for the boundary on useful exergy. Also, the RAT method has a consistency problem because it is difficult to extend it for other heat uses and for all sub-sectors of industry, such as manufacturing, and it does not differentiate between the different energy resources and the different energy (and non-energy) uses.

4. Discussion and Conclusions

Societal exergy studies have much to offer in terms of (1) broadening scientific understanding of energy use and economic growth and (2) provide a more consistent basis for prioritising action to improve energy efficiency and assist the development of improved scenarios of future energy and GHG emissions. However, the current situation is that studies exhibit wide variation in assumptions and methods. This paper has highlighted and synthesized major differences in the methodologies used to account for societal exergy consumption. Broadly, these include differences in the characterisation of input and output flows, different methods of allocating useful exergy to end uses, and different methods of estimating the exergy efficiencies of these end uses. We have provided a wide-ranging and in-depth discussion on each of these points, with the aim of providing clarification for those undertaking future societal exergy analyses. We argue that when forming national exergy accounts, there are three main key issues to address, which are now set out in Sections 4.1–4.3.

4.1. Aims, Inputs and End-uses

As highlighted in column 4 of Table 1, societal exergy analysis has been used for a variety of purposes, which have developed over time. Some examples of these include:

1. Characterising national systems of energy provision to identify where the most significant opportunities for energy savings lie (EF in Table 1).
2. Obtaining a full picture of the efficiency of natural resource use in the economy (EF).
3. Studying the effect of long-run energy transitions (ET in Table 1).
4. Analysing the relationship between energy use and economic growth (EG in Table 1).
5. Forecasting future energy demand (FED in Table 1).

The intended outcome of the study, as well as the availability of data (see Appendix), will determine many characteristics of the methodology employed. If the focus is on energy efficiency or energy uses (e.g. 1, 3, and 4 above), then only the energy resources used to provide an energy service should be included. However, if the focus is on forecasting future needs of primary or final energy (e.g. 5 and 6 above), then energy resources related to non-energy uses should be taken into account. Currently, non-energy uses of energy resources commonly represents

⁹ These authors estimate final to useful instead of primary to useful efficiencies; however the difference is negligible because electricity is not allocated to high temperature heat uses.

around 5% of total primary energy supply (TPES), though their relative importance is growing (Brockway et al., 2014; Serrenho et al., 2014). If the focus of the study is on resource accounting and efficiency of resource use, then materials flows other than energy resources (see Section 2.1) should also be taken into account.

There has also been significant variation in number and scope of end-uses included within previous research. Categories for energy end-uses include: mechanical work, heating (high, medium and low temperature), light, cooling, other electric uses and muscle work. Again, the choice of categories to consider depends on the aim of the study and on the availability of data. For example, the inclusion of physical human labour as a measure of useful exergy may be unwarranted if we want to econometrically test the importance of exergy for growth, as (1) standard economic models already account for labour in different ways, and (2) the importance of human labour may vary depending on the type of economy being modelled (e.g. agrarian, industrial, post-industrial). On the other hand, if the study aims at understanding long-run transitions in energy use or the importance of energy in agriculture, then the energy consumed and provided by working animals and humans should be accounted for. Regarding electrical cooling, its impact might become more important as countries become richer and increase their cooling demand. In this case, the decision on whether to isolate cooling as a separate part of the accounting study should depend on the difficulties of gathering information regarding this energy use. For studies that include all natural resources (including raw materials), end-uses include not only heat, mechanical work and lighting among other energy end-uses but also the useful exergy embedded in materials such as paper and wood or steel. This option comes with a cost, which is the loss in distinguishing the various energy end-uses in material production.

4.2. Electricity

The second major issue regards the characterisation and treatment of electricity within studies. As discussed, the versatility of electricity presents a challenge in allocating final exergy to end uses. (Brockway et al., 2014) and (Serrenho et al., 2014; Serrenho et al., 2016) have provided the most developed treatment of electricity end uses to date.

In addition, the method used to estimate the primary exergy of renewable electricity also yields significant variance on estimated total primary exergy and the aggregate primary to final exergy efficiencies. The Partial Substitution Method (PSM) is a good option when the focus is on efficiency of the economic system (excluding the energy sector) because it disregards changes in the power generation mix. It is also a good option to evaluate the amount of fossil energy that is being “saved” by using renewable electricity. When the focus of the study is the energy sector, it is appropriate to distinguish between fossil fuels and renewables to emphasize temporal or mix-related changes in the efficiency of producing electricity. The Physical Content Method (PCM) and the Resource Content Method (RCM) are good options in this case; PCM penalizes renewable electricity less than fossil electricity (with the exception of geothermal electricity, which has lower efficiencies in the case of PCM). However, unlike the RCM its use in time series studies precludes the ability to include improvements in the conversion efficiency of renewable energy technologies over time. A detailed discussion on these methods that could help in choosing the best option is presented elsewhere (Cegonho and Delgado Domingos J J, 2012; Cegonho et al., 2012; Harmsen et al., 2011; Lightfoot, 2007). These methods convert electricity to primary energy; when converting primary energy to primary exergy care must be taken in the case of heat (e.g. geothermal heat or nuclear heat).

4.3. Granularity and Consistency of Exergy Efficiencies

The third issue is the consistency in the definition and estimation of exergy efficiencies between the final and useful stages of energy use.

The main factors controlling the accuracy of the estimates of exergy efficiencies are the existence and quality of data on: (1) the time-independent allocation of energy resources-sectors (excluding electricity) to end-uses, (2) the time-dependent allocation of the pair electricity-sector to end-uses (i.e. what electricity is being used for in different sectors in each year), (3) time-dependent first-law efficiencies and process temperatures for different industries. For the first topic, for studies after 1960, the IEA databases provide a robust and consistent input mapping method, and as such are being increasingly adopted (Brockway et al., 2014). For the second and third topics, individual country-level data is needed, which is time-consuming, or less ideal proxies can be taken from other published studies or country-data (see Appendix A).

There are also significant differences between studies regarding the consistency on the definition and estimation of exergy efficiencies. Proxies for the exergy efficiency are used when (1) useful outputs – e.g. light, sound and information – are not typically measured in energy units and (2) for cases where lack of data on the useful exergy (e.g. the mechanical work at the shaft in an automobile) is replaced by data on the energy service (mpg). Differences between exergy efficiencies for HTH and for mechanical work (in transport) calculated by studies that use the standard definitions and studies that use proxies are significant (as illustrated in this paper). Additionally, there are other issues that affect the results obtained for exergy efficiencies such as the disagreement regarding the way useful exergy should be measured for the industrial sector; with some authors arguing that it should be measured not as the heat, motion and light delivered in the factory, but instead as the much smaller amount of embedded exergy in the material.

Standard thermodynamic definitions should be used to estimate exergy efficiencies where possible, because other methods are not consistent across several end-uses and differences between exergy efficiencies yielded by different methods are significant. The use of proxies that extend the boundary of useful exergy into exergy services fails to assess whether overall increases in efficiency from final energy to energy services (litres per passenger-km) are due to increases in the thermodynamic efficiency of conversion devices (e.g. more efficient engines) or in the passive systems (e.g. better aerodynamics and less rolling resistance). Additionally, for the sake of consistency and accuracy, exergy efficiencies should (but currently do not) include secondary exergy services associated such as in-car heating or air conditioning.

Acknowledgements

We are grateful to the Portuguese Science Foundation for the sabbatical grants SFRH/BSAB/105941/2015 (Tânia Sousa) and SFRH/BSAB/105943/2015 (Tiago Domingos), the Jan Wallanders and Tom Hedelius foundation for the grant P2015-0275:1 (Sofia Henriques), and the Tore Brodwalhds foundation for the grant F2015-0534:1 (Sofia Henriques), and the Centre on Innovation & Energy Demand for a PhD studentship (Jack Miller). Additionally, we gratefully acknowledge the support of the Engineering and Physical Sciences Research Council (EPSRC) and Arup for contributing to the Ph.D. CASE (Collaborative Award in Science and Engineering) scholarship under grant reference EP/K504440/1 of Paul Brockway. In the latter stages of this paper Paul Brockway's time was funded as part of the research programme of the UK Energy Research Centre (UKERC), supported by the UK Research Councils under EPSRC award EP/L024756/1. The authors thank the discussions with and comments from Julia Steinberger, Steve Sorrell, Peter Taylor and Timothy Foxon.

Appendix A. Appendix

For studies that use primary or final energy from 1960 onwards, the most comprehensive source of data is the IEA database for OECD and over 100 non-OECD countries (data for the latter beginning in 1971). This is illustrated by Serrenho et al. (2014), who use the datasets to obtain useful exergy accounts of 15 European countries between 1960 and

2009. The IEA disaggregates final energy uses per energy resource into fourteen individual industrial sectors, agriculture, services, transportation and households. To be able to do useful energy/exergy calculations' using this dataset, an allocation between values of final energy and end-uses is needed (Brockway et al., 2014; Serrenho et al., 2014). The most problematic resource regarding the specification of end-uses is electricity, because of its ubiquity and the fact that its use has been changing in time.

For longer timespans (i.e. before 1960) data is harder to find, and must be sourced typically from individual country data. It is much easier to find pre-1960 data on primary energy because with a few exceptions such as Fouquet (2008) and others (see Table 1) the great majority of national long-run energy studies focus only on primary energy use (Csereklyei et al., 2014; Gales et al., 2007; Henriques, 2011; Henriques and Borowiecki, 2014; Kander et al., 2013; Krausmann and Schandl, 2008; Kuskova et al., 2008; Schurr and Netschert, 1960). Many of these studies also include, besides fossil fuels and electricity, complex and laborious historical estimates of traditional forms of energy, such as firewood and peat, direct water and wind and muscle energy.¹⁰ However, to be able to estimate useful exergy from this data, we also need to collect information on their distribution end-uses and historical efficiencies, which is complex and time-consuming.

For pre-1960 studies, most of the data that would help allocate energy by end-uses lies in national sources such as industrial censuses, utilities reports, household surveys or transport and agriculture statistics. The time consuming process of collecting such data has so far precluded the development of a comprehensive set of national studies. Nevertheless, there are some international statistics compilations that are helpful in the allocation of end-uses. For example, Mitchell (1962, 2007a, 2007b, 2007c) includes historical output series for almost all countries in the world for some key industries, such as iron and steel, aluminum, mining or chemicals and electricity; transport data such as tonnage of ships and railway freight; and numbers for livestock and the labour force. This data, coupled with some knowledge about the evolution of historical energy efficiencies (Ayres and Warr, 2009; Fouquet, 2008; Kander et al., 2013; Smil, 2001) could be used to estimate proxies for missing energy data. De Stercke (2014) provides a good example of such an approach.

References

- APS, 2008. Energy Future: Think Efficiency. American Physical Society.
- Ayres, R.U., Warr, B., 2005. Accounting for growth: the role of physical work. *Struct. Chang. Econ. Dyn.* 16, 181–209.
- Ayres, R., Warr, B., 2009. *The Economic Growth Engine: How Energy and Work Drive Material Prosperity*. Edward Elgar, Cheltenham.
- Ayres, R.U., Ayres, L.W., Warr, B., 2003. Exergy, power and work in the US economy, 1900–1998. *Energy* 28, 219–273.
- Brockway, P., Barrett, J., Foxon, T., Steinberger, J., 2014. Divergence of trends in US and UK aggregate exergy efficiencies 1960–2010. *Environ. Sci. Technol.* 48, 9874–9881.
- Brockway, P., Steinberger, J.K., Barrett, J., Foxon, T.J., 2015. Understanding China's past and future energy demand: an energy efficiency and decomposition analysis. *Appl. Energy* 155, 892–903.
- Brockway, P., Dewulf, J., Kjølstrup, S., Siebentritt, S., Valero, A., Whelan, C., 2016. In a resource-constrained world: Think exergy not energy. Report D/2016/13.324/5 Published by Science Europe, Brussels.
- Carnahan, W., Ford, K.W., Prosperetti, A., Rochlin, G.I., Rosenfeld, A., Ross, M., Rothberg, J., Seidel, G., Socolow, R., 1975. Second-law efficiency: The role of the second law of thermodynamics in assessing the efficiency of energy use. AIP Conference Proceedings. AIP Publishing, Princeton, pp. 25–51.
- Cegonha, N., Delgado Domingos J.J., D., T., 2012. Um novo método de cálculo de energia primária e a sua aplicação a Portugal. *Actas MEFTE 2012 - IV Conferência Nacional em Mecânica dos Fluidos, Termodinâmica e Energia*, Lisboa.
- Cegonha, N., Delgado Domingos, J.J., Domingos, T., 2012. Um novo método de cálculo de energia primária e a sua aplicação a Portugal. *Actas MEFTE 2012 - IV Conferência Nacional em Mecânica dos Fluidos, Termodinâmica e Energia*, Lisboa.
- Chen, G., Chen, B., 2009. Extended-exergy analysis of the Chinese society. *Energy* 34, 1127–1144.
- Csereklyei, Z.M., Rubio, D.M., S., D.I., 2014. Energy and Economic Growth: The Stylized Facts. Centre for Climate Economics & Policy, Crawford School of Public Policy, The Australian National University.
- Cullen, J., Allwood, J., 2010a. The efficient use of energy: tracing the global flow of energy from fuel to service. *Energy Policy* 38, 75–81.
- Cullen, J.M., Allwood, J.M., 2010b. Theoretical efficiency limits for energy conversion devices. *Energy* 35, 2059–2069.
- Cullen, J.M., Allwood, J.M., Borgstein, E.H., 2011. Reducing energy demand: what are the practical limits? *Environ. Sci. Technol.* 45, 1711–1718.
- De Stercke, S., 2014. Dynamics of Energy Systems: A Useful Perspective. International Institute for Applied Systems Analysis (IR-14-013).
- Dewulf, J., Valero, A., Brockway, P., Barrett, J., 2015. A common scale for our common future: exergy, a thermodynamic metric for energy. Recommendations from the Science Europe Physical Chemical and Mathematical Sciences Committee. Report D/2015/13.324/6 published by Science Europe, Brussels.
- Ertesvag, I.S., 2001. Society exergy analysis: a comparison of different societies. *Energy* 26, 253–270.
- Ertesvag, I.S., Mielnik, M., 2000. Exergy analysis of the Norwegian society. *Energy* 25, 957–973.
- Fluck, R., 1992. Energy of human labour. In: Fluck, R. (Ed.), *Energy in Agriculture. Energy in farm production*. Elsevier, Amsterdam, pp. 31–43.
- Ford, K.W., Rochlin, G.J., Socolow, R.H., Hartley, D.L., Hardesty, D.R., Lapp, M., Dooher, J., Dryer, F., Berman, S.M., Silverstein, S.D., Ross, M., 1975. *Efficient Use of Energy*. American Institute of Physics, New York, USA.
- Fouquet, R., 2008. *Heat, Power and Light: Revolutions in Energy Services*. Edward Elgar Pub, Cheltenham and Northampton, MA.
- Fruehan, R., Fortini, O., Paxton, H., Brindle, R., 2000. Theoretical Minimum Energies to Produce Steel for Selected Conditions. US Department of Energy, Office of Industrial Technologies, Washington, DC, USA.
- Gales, B., Kander, A., Malanima, P., 2007. North versus south: energy transition and energy intensity in Europe over 200 years. *Eur. Rev. Econ. Hist.* 11, 219–253.
- Guevara, Z., Sousa, T., Domingos, T., 2016. Insights on energy transitions in Mexico from the analysis of useful exergy 1971–2009. *Energies* 9, p. 29.
- Häfele, W., 1977. On energy demand. *IAEA Bull.* 19, 17.
- Hammond, G., Stapleton, A., 2001. Exergy analysis of the United Kingdom energy system. *Proc. Inst. Mech. Eng. A J. Power Energy* 215, 141–162.
- Hansson, N., 1928. *Husdjurens utfodring. Dess teoretiska grunder och ekonomiska genomförande*. C.E. Fritze, Stockholm.
- Harmsen, R., Wesselink, B., Eichhammer, W., Worrell, E., 2011. The unrecognized contribution of renewable energy to Europe's energy savings target. *Energy Policy* 39, 3425–3433.
- Henriques, S.T., 2011. Energy Transitions, Economic Growth and Structural Change: Portugal in a Long-run Comparative Perspective. Lund University, Lund.
- Henriques, S.T., Borowiecki, K., 2017. The Drivers of Long-run CO₂ Emissions in Europe, North America and Japan since 1800. *Energy Policy* 101, 537–549.
- Kander, A., Warde, P., 2011. Energy availability from livestock and agricultural productivity in Europe, 1815–1913: a new comparison. *Econ. Hist. Rev.* 64, 1–29.
- Kander, A., Malanima, P., Warde, P., 2013. *Power to the People: Energy in Europe Over the Last Five Centuries*. Princeton University Press, Princeton, NJ.
- Klein, S., Nellis, G., 2012. *Thermodynamics*. Cambridge University Press.
- Krausmann, F., Schandl, H., P., S.R., 2008. Socio-ecological regime transitions in Austria and the United Kingdom. *Ecol. Econ.* 65, 187–201.
- Kuskova, P., Gingrich, S., Krausmann, F., 2008. Long term changes in social metabolism and land use in Czechoslovakia, 1830–2000: an energy transition under changing political regimes. *Ecol. Econ.* 68, 394–407.
- Laitner, J.A.S., Nadel, S., Elliott, R.N., Sachs, H., Khan, A.S., 2012. The Long-term Energy Efficiency Potential: What the Evidence Suggests. American Council for an Energy-Efficient Economy, Washington DC.
- Lightfoot, H., 2007. Understand the three different scales for measuring primary energy and avoid errors. *Energy* 32, 1478–1483.
- Mitchell, B.R., 1962. *Abstract of British Historical Statistics*. Cambridge University Press, Cambridge.
- Mitchell, B.R., 2007a. *International Historical Statistics: Africa, Asia and Oceania 1750–2005*. Cambridge University Press, Cambridge.
- Mitchell, B.R., 2007b. *International Historical Statistics: Europe 1750–2005*. Cambridge University Press, Cambridge.
- Mitchell, B.R., 2007c. *International Historical Statistics: the Americas: 1750–2005*. Cambridge University Press, Cambridge.
- Nakićenović, N., Gilli, P., Kurz, R., 1996. Regional and global exergy and energy efficiencies. *Energy* 21, 223–237.
- Palma, M., Sousa, T., Guevara, Z., 2016. How much detail should we use to compute societal aggregated exergy efficiencies? *Energies* 9.
- Patterson, M.G., 1996. What is energy efficiency? Concepts, indicators and methodological issues. *Energy Policy* 24, 377–390.
- Pimentel, D., Pimentel, M., 2008. *Food, Energy and Society*. Taylor and Francis, New York.
- Reistad, G., 1975. Available energy conversion and utilization in the United States. *J. Eng. Power* 429–434.
- Rosen, M., 1992. Evaluation of energy utilization efficiency in Canada using energy and exergy analyses. *Energy* 17, 339–350.
- Rosen, M., Dincer, I., 1997. Sectoral energy and exergy modeling of Turkey. *J. Energy Resour. Technol.* 119, 200–204.
- Santos, J., Domingos, T., Sousa, T., St. Aubyn, M., 2016. Does a small cost share reflect a negligible role for energy in economic production? Testing for aggregate production functions including capital, labor, and useful exergy through a cointegration-based method. *Ecol. Econ.* (submitted).

¹⁰ Estimates for traditional energy resources are difficult, since many energy sources were not directly recorded. Firewood and peat are usually estimated from household surveys, forest fellings or taxation records. Wind and water power rely on windmill and watermill figures and estimations of their power, time of use and efficiency and animal power relies on livestock numbers and their estimated feed requirements.

- Sassoon, R.E., Hermann, W.A., Hsiao, I.-C., Miljkovic, L., Simon, A.J., Benson, S.M., 2009. Quantifying the flow of exergy and carbon through the natural and human systems. *Mater. Res. Soc. Symp.*
- Schaeffer, R., Wirtshafter, R.M., 1992. An exergy analysis of the Brazilian economy: from energy production to final energy use. *Energy* 17, 841–855.
- Schroll, H., 1994. Energy flow and ecological sustainability in Danish agriculture. *Agric. Ecosyst. Environ.* 51, 301–310.
- Schurr, S.H., Netschert, C., 1960. *Energy in the American Economy 1850–1975: An Economic Study of Its History and Prospects*. The Johns Hopkins Press, Baltimore.
- Sciubba, E., 2005. Exergo-economics: thermodynamic foundation for a more rational resource use. *Int. J. Energy Res.* 29, 613–636.
- Serrenho, A., Sousa, T., Warr, B., Ayres, R., Domingos, T., 2014. Decomposition of useful work intensity: the EU (European Union)-15 countries from 1960 to 2009. *Energy* 76, 704–715.
- Serrenho, A.C., Warr, B., Sousa, T., Ayres, R.U., Domingos, T., 2016. Structure and dynamics of useful work along the agriculture-industry-services transition: Portugal from 1856 to 2009. *Struct. Chang. Econ. Dyn.* 36, 1–21.
- Smil, V., 1994. *Energy in World History*. Westview Press, Colorado.
- Smil, V., 2001. *Enriching the Earth: Fritz Haber, Carl Bosch and the Transformation of World Food Production*. The MIT Press, Cambridge, MA.
- Stanhill, G., 1980. The energy cost of protected cropping: a comparison of six systems of tomato production. *J. Agric. Eng. Res.* 25, 145–154.
- Stout, B.A., 1979. *Energy for World Agriculture*. Food and Agriculture Organization of the United Nations, Rome.
- Stout, B.A., 1990. *Handbook of Energy for World Agriculture*. Elsevier, New York.
- Thomas, J., 2014. Drive cycle powertrain efficiencies and trends derived from EPA vehicle dynamometer results. *SAE Int. J. Passenger Cars Mech. Syst.* 7, 1374–1384.
- Wall, G., 1987. Exergy conversion in the Swedish society. *Resour. Energy* 9, 55–73.
- Wall, G., 1990. Exergy conversion in the Japanese society. *Energy* 15, 435–444.
- Wall, G.E., Sciubba, E.V., 1994. Exergy use in the Italian society. *Energy* 19, 1267–1274.
- Wall, G., Sciubba, E., Vincento, N., 1994. Exergy use in the Italian society. *Energy* 19, 1267–1274.
- Warde, P., 2007. *Energy Consumption in England & Wales 1560–2000*. Consiglio Nazionale delle Ricerche, Naples.
- Warr, B., Ayres, R., 2012. Useful work and information as drivers of economic growth. *Ecol. Econ.* 73, 93–102.
- Warr, B., Schandl, H., Ayres, R.U., 2008. Long term trends in resource exergy consumption and useful work supplies in the UK, 1900 to 2000. *Ecol. Econ.* 68, 126–140.
- Warr, B., Ayres, R.U., Eisenmenger, N., Krausmann, F., Schandl, H., 2010. Energy use and economic development: a comparative analysis of useful work supply in Austria, Japan, the United Kingdom and the US during 100 years of economic growth. *Ecol. Econ.* 69, 1904–1917.
- Williams, E., Warr, B., Ayres, R., 2008. Efficiency dilution: long-term exergy conversion trends in Japan. *Environ. Sci. Technol.* 42, 4964–4970.
- Wirsenius, S., 2000. *Human Use of Land and Organic Materials: Modelling the Turnover of Biomass in the Global Food System*. Department of Physical Resource Theory, Gothenburg (Phd Thesis).
- Worldsteel, 2015. *Energy Use in the Steel Industry*. World Steel Association, Brussels.